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ЕКСПЕРИМЕНТАЛНО ИЗСЛЕДВАНЕ НА МОДЕЛА НА ЕФЕКТИВНАТА СПЕКТРАЛНА ШИРИНА НА ШУМОВАТА МОЩНОСТ ЗА ОПИСАНИЕ НА ОПТИЧЕН УСИЛВАТЕЛ С ЛЕГИРАНО С ЕРБИЙ ВЛАКНО

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Резюме: *В настоящата работа е изследвана приложимостта на модела на ефективната спектрална ширина на шумовата мощност за описание на характеристиките оптичен усилвател с легирано с ербий влакно. Експериментално са изучени зависимостта на усилването на слаб сигнал от мощността на напомпващото лъчение, както и ефекта на насищане на усилването при големи мощности на сигналното излъчване. Направеното сравнение между числените резултати и получените експериментални данни показва добро съответствие и в двата режима на работа на усилвателя. Това ни позволява да заключим, че моделът използващ ефективната спектрална ширина на шумовата мощност, може успешно да бъде прилаган при анализ на характеристиките на оптичен усилвател с легирано с ербий влакно.*

Ключови думи: *модел на ефективната спектрална ширина на шумовата мощност, оптичен усилвател с легирано с ербий влакно*

EXPERIMENTAL RESEARCH OF THE MODEL OF THE EFFECTIVE BANDWIDTH OF THE AMPLIFIED SPONTANEOUS EMISSION FOR THE DESCRIPTION OF AN OPTICAL AMPLIFIER WITH ERBIUM-DOPED FIBER

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Abstract: *In this paper we have researched the applicability of the model of the effective bandwidth of the amplified spontaneous emission for the description of the characteristics of an optical amplifier with erbium-doped fiber (EDFA). Experimentally, we have studied the dependence of the gain of a small signal on the power of the pumping light, as well as the effect of gain saturation when the signal power grow up. The comparison we have made between the numerical results and the experimental data derived, shows a good correspondence in both operation modes of the amplifier. This allows us the conclusion that the researched numerical model can be used successfully in the analysis of the characteristics of an optical amplifier with erbium-doped fiber.*

Key words: *model of the effective bandwidth of the amplified spontaneous emission, EDFA*

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1. Introduction

The amplifiers with erbium-doped fiber (EDFA) have gained ground in the wave division multiplexed multi-channel optical communication systems as well as in the broadband cable communication systems (CATV) [1-6]. The reason for this are their parameters in the C band $(1525 \div 1565\, nm)$: high gain $(30 \div 50\, dB)$, broad spectral band $(\approx 90\, nm)$, low noise coefficient $(3 \div 5\, dB)$, high level of the output signal $(10 - 20\, dBm)$.

The EDFA operation principle is based on the absorption of pumping laser light from the erbium ions doped in the fiber and its reemission in the form of stimulated emission in the amplified optical signal. The stimulated emission defines the optical gain of the amplified optical signal. An amplified spontaneous emission (ASE) appears which defines the noise properties of the amplified signal [1-3].

There are three schemes for optical (laser) pumping of EDFA: same direction, opposite direction and both direction. In the first case, the direction of the pumping light corresponds to the direction of the amplified optical signal, while in the second case these directions are opposite. For the both direction pumping two pumping lights are used. One is given at the beginning of the fiber parallel to the direction of distribution of the amplified signal (forward pump), and the other – at the end of the fiber in a direction opposite the direction of distribution of the amplified signal (backward pump).

For the modeling of optical amplifiers on the basis of erbium-doped fiber is used a system of equations describing the distribution of the signals, the pumping and noise powers along the fiber and equations defining the modification speed of erbium ion energy levels populations [1-2]. For the description of the population of the two levels, a model with two levels of the erbium ions in its stationary approximation [1-2] is used. The existing numerical methods for the analysis of the EDFA characteristics have been considered in detail in [1,2,4]. In the most detailed model the spontaneous emission has been described by using many signals (each with spectral width, for example $1\, nm$), which are being distributed in the two directions along the fiber (forward ASE and backward ASE) [3]. This model allows for the detailed research of the complex interrelation between amplified signal, pumping light, generated spontaneous emission (forward ASE and backward ASE), and relative concentration of the active erbium ions [2].

A simple way of measuring the spontaneous emission is the model of the effective spectral width of the noise power [4]. In this model, the spontaneous emission is presented by two signals distributed in opposite directions, each with an equal effective spectral width [4]. We will mark the signal distributed in the direction of signal distribution (forward ASE) with P_{ASE}^{+}, and the one distributed in the opposite direction (backward ASE) with P_{ASE}^{-}. Using typical values of the parameters of the task, we have researched numerically in [7] the applicability of the effective spectral width of the noise power [4] for the correct description of the features of the gain. It has been shown that the dependencies derived in [7] are well-coordinated with those presented in [2] and derived by the full approach.

The aim of this paper is to check the applicability of the model of the effective bandwidth of the amplified spontaneous emission when its results are compared to those derived by the experimental research of an optical amplifier with the erbium-doped fiber. In this sense, the paper includes two sub-aims. The first one is the experimental research of the amplifier characteristics. The second one is the comparison between the experimental results with the numerical results derived using the noise power effective spectral width model [4].

2. Description and characteristics of the experimental setting and the numerical model

In this paragraph we have set two goals. First, we have presented a description of the existing in Department of Physics of TU-Sofia optical amplifier on the basis of erbium-doped fiber (EDFA) and the implemented empirical scheme for the experimental research of its characteristics. Second, we have introduced the basic equations for the modeling of the amplifier. Special attention has been given to the connecting of the model parameters to the data known for the particular erbium-doped fiber.

Description of the experimental setting

From the company „Amonics”- Hong Kong was delivered in TU-Sofia a fiber amplifier containing the following basic components: a) signal semiconductor laser with distributed feedback (DFB) with basic frequency of 1560 nm with adjustable power up to 1.5 mW. There is an option for temperature readjustment of the generated frequency within the range of 1550-1562 nm.; b) semiconductor pumping laser at the frequency of 980 nm with adjusting power up to 155 mW, additionally provided with an optical power meter; c) erbium-doped fiber (EDF) of the type R37103 with length 2.5 m; and d) photoreceiver. The additional components are: WDM 980/1550 multiplexer, optical isolators at 1550 nm, optical filter at 1560 nm and FC/UPC connectors. There is an option for the connection of a spectral analyzer by an additional connector.

The scheme for connection of all the above components, implementing EDFA is shown in fig. 1.

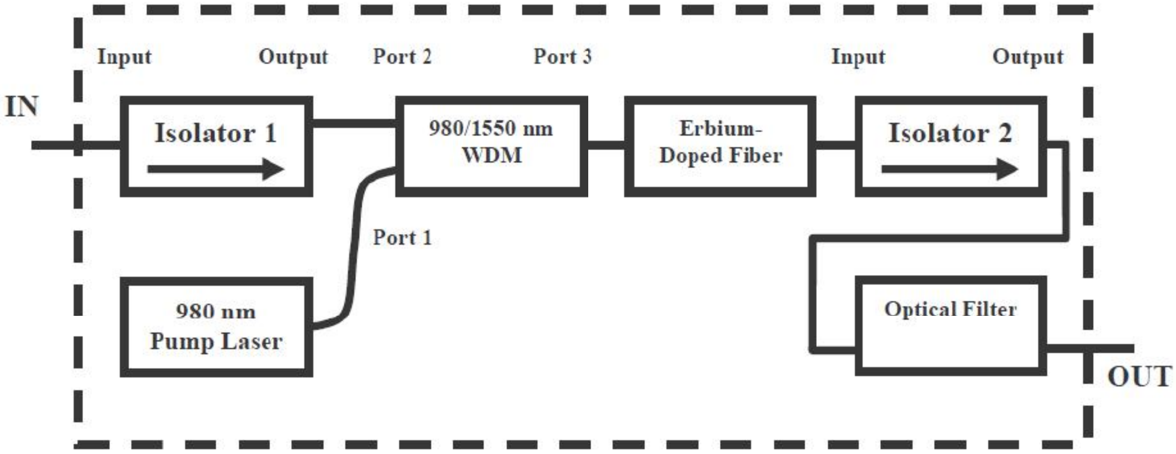

Fig.1. Mount scheme of the erbium-doped optical amplifier. The signal laser and the detector are connected respectively to the connections marked with IN and OUT.

The scheme presented in fig. 1 works as follows. At the entrance marked as IN is given the signal emission from the semiconductor DFB laser at wavelength 1558-1562nm. The function of isolator-1 is to stop the going back of a reflected light to the signal laser at its operation frequency. The function of the WDM-multiplexor is to gather the signal wavelength λ=1560nm and the pumping wavelength λ=980nm generated by the pumping semiconductor laser in EDF. Isolator-2 stops the going back of a reflected light to EDF. The filter is used to filter ASE around the signal frequency and make easier the defining of the signal output power. The signal from the output marked as OUT enters the optical detector measuring the power of the optical emission.

The fiber R37103 [8] used in the EDFA is additionally alloyed with aluminum and lanthanum. With the additional alloying are reduced the effects from the higher erbium ion concentration and the OH-induced losses. The saturation's parameter of the fiber according to the manufacturer's data is $\xi = 1.03\times10^{16}(ms)^{-1}$, which means that the concentration of erbium ions is $N_0 \approx 1.364\times10^{25}\,m^{-3}$. The spectral dependences of the absorption $\alpha(\lambda)$ and gain $g(\lambda)$ coefficients of the fiber, given by the manufacturer, are shown in fig. 2.

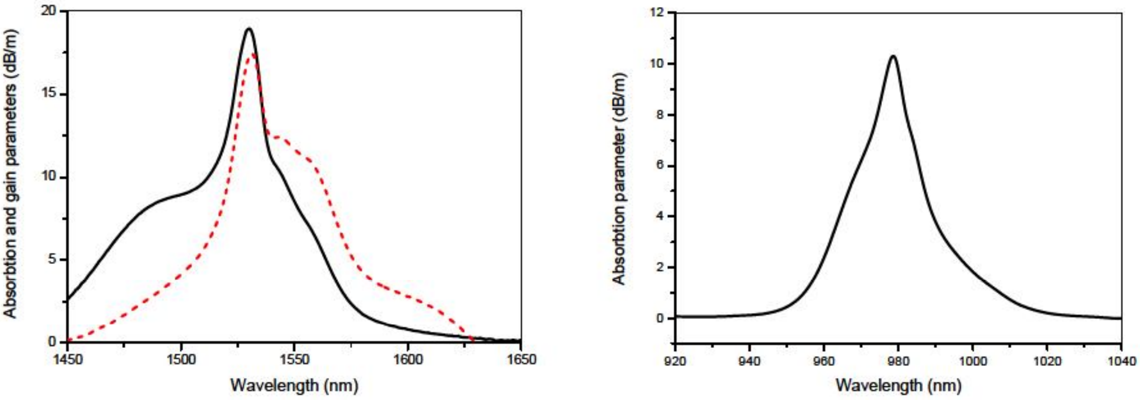

Fig. 2. The spectral dependence of the absorption $\alpha(\lambda)$ and gain $g(\lambda)$ coefficients the fiber R37103 in the signal spectral area C and L-band (on the left) and in the area of pumping (on the right) [8].

Other parameters of the fiber are given in table 1 [8].

Diameter of the core (typical)	3.1 µm
Diameter of the cladding	125 ± 0.7 µm
Diameter of the coating	245 ± 10 µm
Peak value of the absorbtin @ 1530 nm	16 - 24 dB/m
Cutoff frequency	840 - 960 nm
Numerical aperture	0.25 ± 0.02
Diameter of the mode	5.4 ± 0.5 µm
Losses at 1200 nm	<10 dB/km

Table 1. Mechanical and physical parameters of the fiber R37103

3. Numerical modeling of the equation system describing the distribution of the pumping, signal and noise power.

For the modeling of the EDFA is used a set of equations describing the distribution of the signals, the pumping and noise power along the fiber, and equations defining the modification speed of the erbium ion energy level populations [1,2]. For a description of the population of the two levels is used a model with two levels of the erbium ions in it stationary approximation [1,2].

In this paper we have studied the gain of one signal with wavelength $\lambda_S = 1560\,nm$, whose power will be marked by P_S. We use pumping laser with wavelength $\lambda_P = 980\,nm$, whose power is marked by P_P^+.

For the description of the spontaneous emission we have used the model of the effective bandwidth of the amplified spontaneous emission. The powers of the two signals with equal effective spectral width are marked by P_{ASE}^+ (forward ASE) and P_{ASE}^- (backward ASE). The equations describing the distribution of the signal, pumping and noise power along the fiber are the following:

$$\begin{aligned}
&\frac{dP_S}{dz} = \Gamma_S\left(\sigma_S^E N_2 - \sigma_S^A\left(N_0 - N_2\right)\right)P_S\\
&\frac{dP_P^+}{dz} = \pm\Gamma_P\left(\sigma_P^E N_2 - \sigma_P^A\left(N_0 - N_2\right)\right)P_P^+\\
&\frac{dP_{ASE}^\pm}{dz} = \pm(\Gamma_S\sigma_S^E N_2 P_0 + \Gamma_S\left(\sigma_S^E N_2 - \sigma_S^A\left(N_0 - N_2\right)\right)P_{ASE}^\pm)
\end{aligned} \qquad (1)$$

where $\Gamma_S$and Γ_P are the factors of overlapping of the respective optical distributions with the part of the fiber which is erbium-doped. σ_S^E, σ_P^E and σ_S^A, σ_P^A are the cross-sections of the transitions when there is emission and absorption for the two wavelengths considered. $N_0\left[ions/m^3\right]$ is the Er^{3+} ion concentration of the fiber core. $N_2\left[ions/m^3\right]$ is the concentration of exited Er^{3+} ions . $P_0 = 2h\nu_S\Delta\nu$ is the power of the spontaneous emission, whose direction is the same as the direction of the amplified signal, h is the Planck's constant, ν_S is the frequency of the amplified signal. In correspondence with [4] we have assumed that $\Delta\nu = 1250\,GHz\ (\Delta\lambda = 10nm)$. The same is the width of the frequency band of transmission of the optical filter in the output of the amplifier. Because we have considered a short erbium-doped fiber, the attenuation of the signals has not been given.

The rate equation in the steady-state approximation of the model with two levels [1-2] relates the ion population density in the upper level $N_2$with the field powers and the total ion density N_0. The N_2 is given by the expression:

$$N_2 = \frac{\dfrac{\tau\sigma_S^A}{Ah\nu_S}\Gamma_S P_S + \dfrac{\tau\sigma_S^A}{Ah\nu_S}\Gamma_S\left(P_{ASE}^+ + P_{ASE}^-\right) + \dfrac{\tau\sigma_P^A}{Ah\nu_P}\Gamma_P\left(P_P^+ + P_P^-\right)}{\dfrac{\tau\left(\sigma_S^E + \sigma_S^A\right)}{Ah\nu_S}\Gamma_S P_S + \dfrac{\tau\left(\sigma_S^E + \sigma_S^A\right)}{Ah\nu_S}\Gamma_S\left(P_{ASE}^+ + P_{ASE}^-\right) + \dfrac{\tau\left(\sigma_P^E + \sigma_P^A\right)}{Ah\nu_P}\Gamma_P\left(P_P^+ + P_P^-\right) + 1} N_0 \qquad (2)$$

where $\tau \approx 10\,ms$ is the lifetime of the metastable energy level ${}^4I_{13/2}$ of Er^{3+}, and A is the effective cross- sectional area of the distribution of erbium ions.

The combined consideration of the equations (1) and (2), means the solution of a boundary problem in two points. The spontaneous emission which is propagated in the distribution direction of the signal P_{ASE}^{+} equals zero at the beginning of the fiber $\left(P_{ASE}^{+}(0)=0\right)$, and the spontaneous emission which is distributed in a direction opposite to the signal distribution P_{ASE}^{-} equals zero at the end of the fiber $\left(P_{ASE}^{-}(L)=0\right)$. The numerical solution of the system of ordinary differential equations (1) and (2) has been done by the Runge-Kutta method, by program products created by using Mathematica software.

The signals considered are distributed in both directions of the fiber, taking into account the limit conditions, while self coordinated solution is found. In this case of forward direction pumping there are 4 signals: amplified signal P_S, pumping signal P_P^{+}, and two noise signals distributed in both directions P_{ASE}^{+} and P_{ASE}^{-}. For the reaching of self coordinated solution it is applied an appropriate iterative procedure. The simplification related to the application of the noise power effective spectral bandwidth model is the result of the smaller number of noise signals – two, but distributed in different directions.

For the calculation of the cross-sections with absorption σ_P^A, σ_S^A and emission σ_S^E, for the wavelengths we are interested in we use the spectral dependencies of the coefficients of absorption and amplification represented in fig. 2 [4]. If the Er^{3+} ions are uniformly distributed in a disk concentric with the fiber core:

$$\sigma_S^A = \frac{\alpha_S}{\Gamma_S N_0}; \sigma_S^E = \frac{g_S}{\Gamma_S N_0}; \sigma_P^A = \frac{\alpha_P}{\Gamma_P N_0} \qquad (3)$$

The values of the parameters of absorption and amplification for the signal and pumping emission are: $\alpha_S = 1.365 m^{-1}$, $\alpha_P = 2.236 m^{-1}$ $g_S = 2.335 m^{-1}$. For the calculation of the factors of overlapping Γ_S and Γ_P we use [2,4]:

$$\Gamma_S = 1 - e^{-2a^2/W_S^2}; \Gamma_P = 1 - e^{-2a^2/W_P^2} \qquad (4)$$

where $a = 1.55 \mu m$ is the fiber core radius (equal of the radius of the erbium-doped area), and W_s, W_p are the radii of the Gaussian approximation of the distributions of the modes for the two emissions. In their turn, W_s, W_p have been calculated by the approximated formula of Desurvire:

$$W_S = a\left(0.759 + \frac{1.289}{V_S^{1.5}} + \frac{1.041}{V_S^{6}}\right); W_P = a\left(0.759 + \frac{1.289}{V_P^{1.5}} + \frac{1.041}{V_P^{6}}\right) \qquad (5)$$

where $V_{S,P} = 2\pi a NA / \lambda_{S,P}$ are the normalized frequencies for the two wavelengths, and NA is the value of the fiber numerical aperture in table 1 $(NA \approx 0.25)$. For the factors of overlapping Γ_S and Γ_P we derive the following values: $\Gamma_S = 0.59, \Gamma_P = 0.81$. Finally, for the cross-sections for absorption and emission, for the wavelengths we are interested in, we derive:

$$\sigma_S^A = 1.69 \times 10^{-25} m^2; \sigma_S^E = 2.89 \times 10^{-25} m^2; \sigma_P^A = 2.02 \times 10^{-25} m^2; \sigma_P^S = 0 \qquad (6)$$

Because it is impossible to measure them accurately, in the numerical model we have not taken into account the losses when the signal and pumping emission is introduced in the fiber, nor the losses when the signal emission is taken out of the fiber and introduced into the detector. This is the possible reason which has led to a difference between the experimentally measured and numerically calculated values of the amplification coefficient of the order of 4 dB. To compensate for these losses, we have introduced respectively two correction parameters k_1 and k_2. Their values $k_1 = 0.29, k_2 = 0.84$ have been derived by comparing the numerical and the experimental data. In the numerical model they have been introduced by correcting the values of the absorption and emission cross-sections as follow: $k_1 x\sigma_P^A; k_2 x\sigma_S^E$. Once defined, those parameters do not change when there is variation of the pumping power or the signal emission in the two amplifier operation modes considered: amplification of a weak signal and saturation of the amplification. Using them leads to a good correspondence (difference up to 10%) between the experimental and numerical results.

4. Comparison between the experimental and the numerical results

In this paragraph we have compared the numerical results derived with the model of the effective bandwidth of the amplified spontaneous emission given by (1) и (2) to the experimental results derived using the experimental setting presented above in the two basic modes of the amplifier: a) when there is small signal gain and b) in a mode of gain saturation.

In the small signal amplification mode, the speed of the transition of the electrons of the metastable $^4I_{13/2}$ level in the erbium is much higher than the speed of the spontaneous emission. In this mode, the amplification remains constant with the increasing of the signal strength. We have studied the following dependencies when there is amplification of a small signal: a) variation of the signal emission power when there are two fixed pumping powers (fig. 3); b) variation of the pumping emission power when there is fixed signal power (fig. 4).

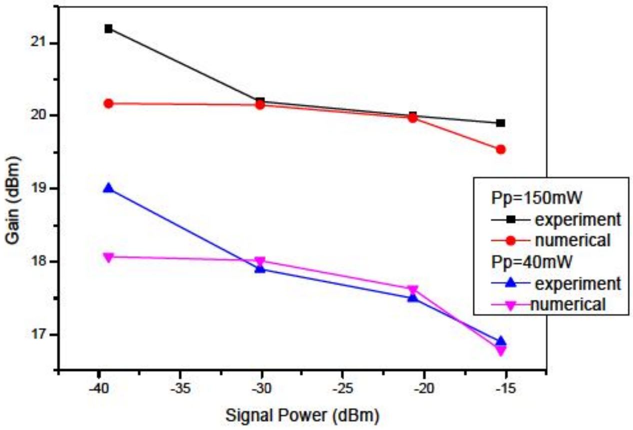

Fig.3. Numerical and experimental data for small signal amplification: variation of the signal emission power when there are two fixed pumping powers 150 and 40 mW.

The maximum difference between the experimental and numerical result exists for signal powers of the order of -39.4dBm and comprises 5.3%. Below we have presented the curves of amplification depending on the pumping power for four fixed signal powers: P_s= -39.4, -30.1, -20.7 and -15.3dBm.

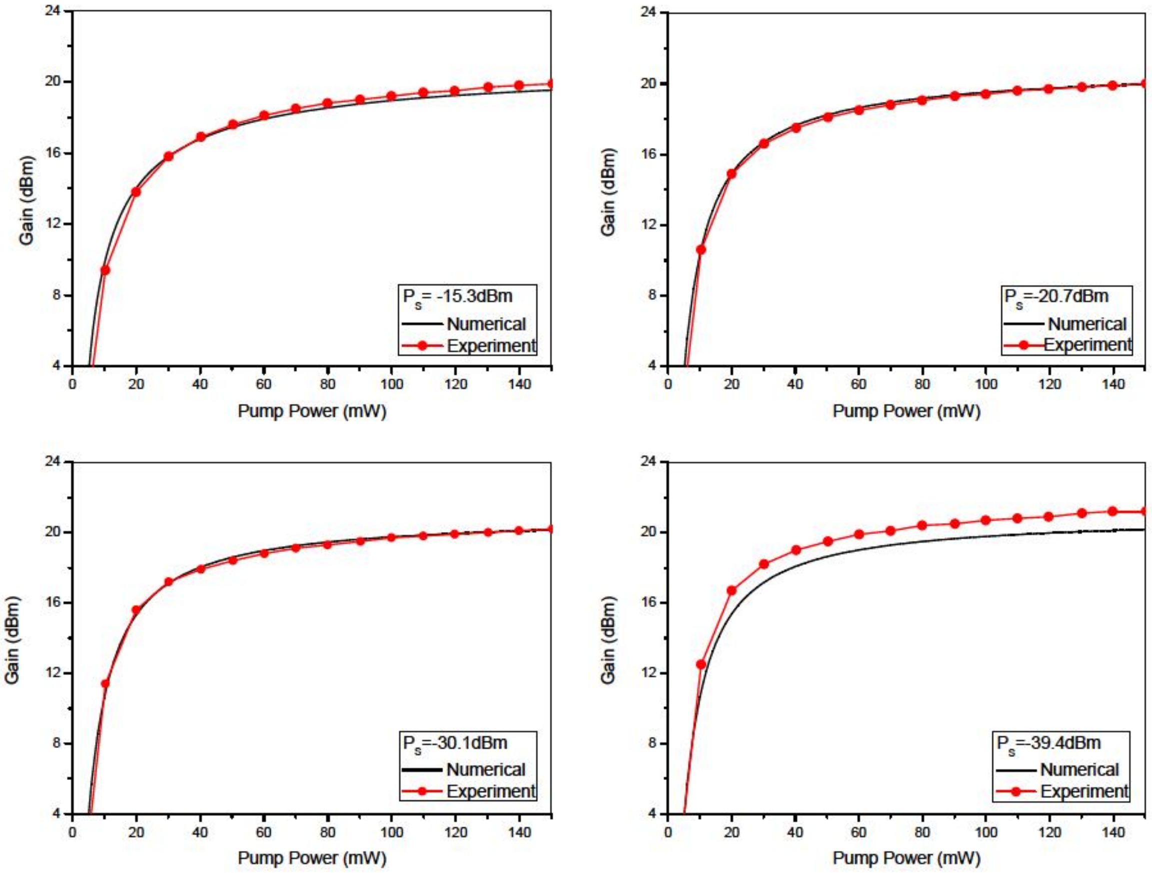

Fig. 4. Numerical and experimental data for the amplification of a weak signal with signal powers (see legend) -15.3, -20.7, -30.1, -39.4dBm and variation of the pumping power.

The comparison between the experimental and numerical results presented in Fig. 4 shows a very good correspondence. On the other hand, the experimental and numerical results derived are well-combined with the published ones known in [2].

In the gain saturation regime the pumping power is high enough to exhaust the basic energy level. In this case, when the signal power is increased, the amplification decreases. Below we have presented dependencies of the amplification on the power of the signal emission when there is fixed pumping power.

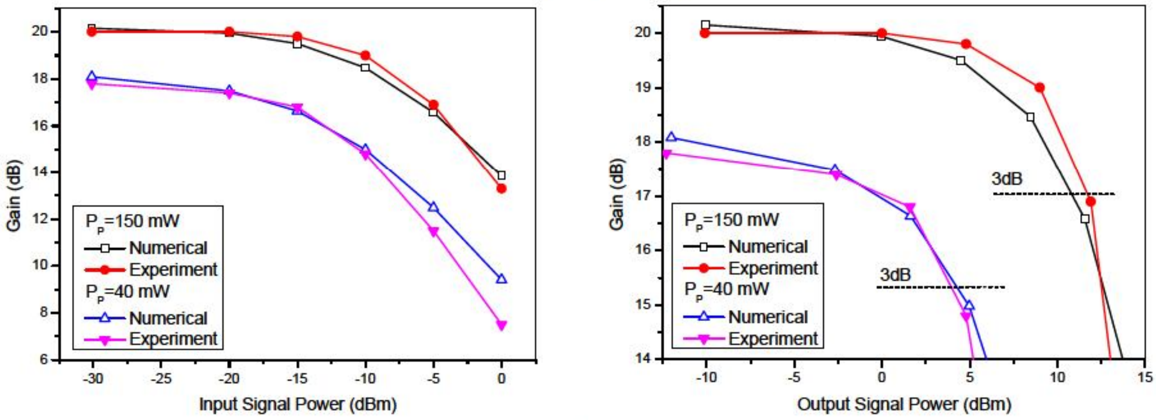

Fig. 5. Numerical and experimental data when there is saturation of the amplification: for fixed pumping powers of 40 and 150 mW: a) (left) dependence of the coefficient of amplification on the power of the input signal; b) (right) power of amplification saturation.

The power of amplification saturation is the power of the output signal when there is fixed pumping power where the amplification decreases by 3 dB. This parameter is an indicator of the amplification saturation in EDFA where further increasing of the signal power leads to sharp decreasing of the amplification. The results from the numerical modeling show that when the pumping emission is 150 mW, the amplification saturation power is ~10.8 dBm, while the experimental data shows as value for this power ~11.7 dBm. When the pumping power has a power of 40 mW, the amplification saturation power is respectively 4.89 dB in the experiment and 5.35 dB in the numerical modeling. The deviation of the numerical data from the experimental data in both the cases presented does not exceed 10%, which means that even in an amplification saturation mode, there is a relatively good quality correspondence between the numerical model and the experimental results.

5. Conclusion

In this paper we have studied the applicability of the model of the effective bandwidth of the amplified spontaneous emission for the description of the characteristics of an optical amplifier with erbium-doped fiber. The comparison made between the basic results derived using this model and the experimental data shows a good quality correspondence in both operation modes of the amplifier: a) amplification of a small signal; and b) in the area of amplification saturation when there are higher powers of the signal emission. On the other hand, both the experimental and numerical results derived here are well-coordinated with the published ones known in [2].

We should not forget that, due to lack of information in our experimental setting on the losses at the time of the insertion of the light into the fiber, and the losses at the time of extraction of the signal out of the fiber and its introduction into the detector in the numerical model, we have introduced two fitting parameters. Irrespective of this circumstance, however, we consider the results presented a reason to claim that the model using the noise power effective spectral width can be applied successfully in the analysis of an optical erbium-alloyed fiber amplifier.

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